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An Alternative Origin of Lake Vostok and Its Exobiological Implications for Mars

Abstract:

In connection with recent Galileo images of the jovian satellite Europa, there has been a significantly increased interest in the sub-glacial Lake Vostok in central East Antarctica. Since the theoretical prediction by Zotikov (1961) of the existence of lakes (one of which later named Vostok) under about 4 km of ice in Antarctica (1) and its confirmation by radar measurements from aircraft in 1974 (2) and from ERS1 satellite in 1993 (3), it has been thought that the lake originated from basal melting of ice. We propose an alternative hypothesis and support it by comprehensive physical and numerical modeling. We suggest that Lake Vostok could have existed on the surface before Antarctic perennial glaciation began 5 - 30 Myrs ago and then was buried under thermally protecting ice. As a result of our computations, we conclude that Lake Vostok has survived the Antarctic glaciation without freezing all the way to the water bottom, if it were initially an open lake with a surprisingly small water depth ($>\approx$ 53 m). The current water depth at a single point is about 500 m (4). The computed critical water depth is applicable to other Antarctic lakes under a thick ice cover.

For an elevated lower heat flow of 100 mW/m^2 (owing to the friction of a glacier against bedrock, (5)) we computed the maximum freezing depth to be $\approx$ 39 m reached in ONLY $\approx$ 1750 years from the onset of Antarctic glaciation. We computed the water depth critical for the lake's survival with the Mars' internal heat flow of 30 mW/m^2 to be $\approx$ 63 m. For the lowest estimate (20 mW/m^2) of Europa's internal heat flow over its history, the freezing front penetrates down to the maximum depth of about 69 m in $\approx$ 8000 years. The existence of the lake before the accumulation of ice in Antarctica implies that possible microorganisms and their remnants in the lake can be OLDER than the Antarctic ice sheet, i.e. older than 5 - 30 Myrs. We also have proposed experimental tests for our hypothesis. Our computations with Mars' internal heat flow are consistent with the possibility of the existence of surface lakes in polar regions before the formation of the martian polar caps. Such environments would be ideal candidates for extant or extinct

life on the red planet. This argues for a drilling mission at the martian polar caps. The interpretation of the most recent Mars Global Surveyor Mars Orbiter Laser Altimeter data supports our model of the origin of possible sub-polar water on Mars versus the old basal melting hypothesis.

Introduction

About 77 lakes have been identified in Antarctica under the kilometers-thick ice cover from airborne radio-echo-sounding data. Nevertheless, most previous studies were concerned with Antarctic lakes under the thin perennial ice of 3.5 - 6.0 m (6-8). These lakes are supersaturated with oxygen and nitrogen (as a result of photosynthetic oxygen production and biological nitrogen production), both ultimately a function of being in a photic zone. Thus such lakes cannot be considered as good analogs for the subsurface water on Europa and Mars, which are separated from light energy by kilometers of ice cover. Secondly, mechanisms of liquid generation for the Antarctic lakes under the km-thick ice are different from the lakes under the m-thick ice, where sunlight plays an important role. Moreover, a lake under the km-thick ice is very interesting from a viewpoint of preserving old species of microorganisms and/or their remnants in the water and sediments, since there has been a long isolation from the exterior. The lower ice of the current 3623 m deep borehole above Lake Vostok (which is only about a hundred meters short of reaching water) is $\approx$ 400,000 years old.

Recent radar imaging of the Lake Vostok's contour by the Canadian satellite RADARSAT (September-October 1997) coincided with the revised interpretation of the seismic data obtained by Russian scientists in 1964 (9). These data are complemented by the radio-altimeter data obtained from a European satellite ERS1 in 1993 and from the earlier radio-echo data taken from airplanes in 1974. They showed that the length of the lake is $\approx$ 230 km and the maximum width is $\approx$ 50 km.

Zotikov (1 , 10) has developed a 1D analytical model of thermal regime of thick ice in central Antarctica above Lake Vostok. The advantage of his model is that it accounts for the heat transport owing to the thick ice spreading by including the term $c\rho V * \nabla T$ into the heat conduction equation. The main assumption of his thermal model is that ice thickness does not change as a function of time. According to this steady-state model, there is a constant basal melting above the central part of Lake Vostok (under the thickest ice) with a rate of about 1 mm/yr (10). This melting is compensated by the ice accumulation on top of the glacier via the snowfall.

To date, the only hypothesis considered for the origin of Lake Vostok was basal melting (e.g., 1, 10, 5, 11). It implies that after accumulation of a sufficiently thick ice, the ice begins to melt at the bottom. Melting starts mainly because the temperature increases with depth. Pressure induced melting is a secondary effect in this case, since the -3.22 C melting temperature at the base of the 3.7 km ice is only a small percentage of the temperature difference between the top (-55 C) and the basal temperatures.

Here we investigate an alternative hypothesis for the origin of Lake Vostok. We propose that there could have been an open lake before the glaciation of Antarctica 5 - 30 Myrs ago. We constructed a numerical model with freezing front dynamics and temperature dependent thermophysical characteristics, considering the problem in a nonlinear Stefan formulation in order to test our hypothesis. As a result of computations, we obtain the critical depth of the initial lake, which is less than the current depth of about 500 m at a single point.

We would like to underscore that the existence of Lake Vostok does not require a hotspot under it even assuming the geothermal basal melting hypothesis. An average geothermal heat flow of about 50 mW/m^2 gives a constant basal melting for an ice sheet thicker than about 2 km (1). The heat flow on the lower boundary has to be doubled, compared to the average geothermal heat flow, if we want to take frictional heating, due to the friction between the spreading ice cap (with the spreading velocity in central part of the cap ≈ 10 m/yr) and the bedrock, into account.

In this report we have numerically supported the hypothesis that the lake existed in an ice-free continent and then survived the glaciation without freezing all the way to the water bottom. Our new hypothesis about the origin of the lake changes the traditional view on the age of possible microorganisms and their remnants in Vostok waters. Our hypothesis implies that Lake Vostok could be an environment, which is older than 5 - 30 Myrs, the age of the Antarctic ice sheet. There is an important issue here that 5 - 30 Myrs is not too long, so that the biota trapped in Vostok is predicted to be bacterial, fungal, animal, and plant. If, on the contrary, the lake originated from meltwater, then probably only soil species of animals a nd plants will be found, along with bacteria. If there is a sufficient geothermal input, then one might expect a productive aquatic environment in proportion to this input. If not, the whole system should be very minimally alive, if at all.

Before the first close-up images of water-ice covered jovian satellite Europa were taken on 19 December 1996, Antarctic lakes under about 4 km of ice were cited as possible analogs for deep subpolar aquifers on Mars (12), especially under the north polar cap. Thermal calculations (13-15) based on the assumed 4 - 6 km thickness of the martian north polar cap, indicated the potential for geothermally-produced basal lakes on Mars, when it becomes sufficiently thick. Recent measurements of Mars Orbiter Laser Altimeter (MOLA) on Mars Global Surveyor implied that the north cap is thinner (maximum thickness about 3 km, 16). than thought before. The cap has an average thickness of 1.03 km. Depending upon the thermal conductivity of the cap, the ice cap of this thickness probably is not enough to have basal melt under it. Applying our Vostok studies to Mars, we offer an alternative hypothesis that there could have been open water lakes near the Martian poles before the formation of the polar caps, and that these lakes have never been frozen to the bottom.

Though the MOLA data on the south polar cap will be obtained only in spring 1999, the south polar ice deposits also appear too thin (1 - 2 km) to have lakes beneath them, assuming the geothermal melting hypothesis (15). Our alternative hypothesis for the lake's origin relaxes the condition on the thickness of Mars's polar cap, i.e. potential subglacial lakes can exist on Mars under much thinner ice than it was thought before, including below the south polar cap. As with Lake Vostok on Earth, our hypothesis has interesting implications for search of life (either extant or extinct) on Mars.

Physical model

We began our modeling with the assumption that we had a lake on the surface of 500 m initial water depth. We considered the nonlinear dynamical problem with two moving boundaries during the early Antarctic glaciation. The upper boundary moves due to the ice accumulation via the snowfall and the lower moving boundary is the phase transition front. In the initial phase there is a freezing front propagating from the top of the water down. The freezing slows down when the upper ice becomes sufficiently thick. Then the front stops and reverses into melting. We have considered the phase transition problem in a complete nonlinear Stefan formulation.

The whole domain, where the problem was solved, was changing in time due to the snowfall on the upper boundary. The lower boundary of our computational domain was fixed in water shortly above the lake sediments. We have incorporated the temperature dependent snowfall rate in our model. The cooler the temperature, the smaller the snowfall rate. To exclude the temperature variable, we have correlated the net ice accumulation rate with the height of the ice accumulated due to snowfall. The net ice accumulation includes snowfall, snow densification into firn and ice sublimation (cf. nitrogen glaciers on Pluto and Triton, 17). To obtain the variable snowfall rate we performed linear interpolation using the two points: the current net ice accumulation rate of 2.4 cm/yr (18), corresponding to the current 3.5 km ice thickness, and the initial rate of 20 cm/yr corresponding to zero thickness.

The initial net rate of 20 cm/yr has been inferred from measurements of the current snowfall rate near the coast of Antarctica (e.g., near lake Figurnoe), where the climate is warmer than in central East Antarctica because of the warming oceanic influence. This should approximate the situation at the beginning of the Antarctic glaciation. Since the ice accumulation due to snowfall an integral of the snowfall rate, which in turn depends upon the ice accumulation, we arrived at an ordinary linear differential equation of the first order. To find the net ice accumulation due to snowfall as a function of time, we solved it analytically and used this solution, which is a non-linear function of time, as an input parameter to our model. The upper boundary temperature on the top of the ice cover was correlated with the glacier thickness, to exclude the time variable. Then we used a linear interpolation to find the upper boundary temperature as a function of the net ice accumulation with the interpolating points being - 12 C (-10 C for another program run) at the initial zero thickness and -55 C at the current 3.5 km ice thickness. As with the initial ice accumulation rate, the initial upper boundary temperature of -12 was chosen in accordance with the measurements of the contemporary yearly averaged ice temperature at the Antarctic coast.

Water ice undergoes pressure induced melting - a behavior opposite to that of N_2 ice and rock. By taking the melting temperature T_{phase}=0 instead of considering pressure induced melting of water ice, one makes freezing faster and hence the worst case scenario is considered. Nevertheless, we have constructed a more complicated model with T_{phase} depending upon pressure. We also included in our model the dependence of thermophysical characteristics upon temperature. Moreover, our algorithm permits consideration of spatial variations in the geothermal heat flow, i.e. to consider a hot spot.

Neither the salinity nor the types of salts (if any) for Lake Vostok are known, thus we did not include the depression of the melting temperature due to this factor. But in no way does this weaken the support for our hypothesis about the origin of the lake. If water is more salty, T_{phase} is lower and instead of the lower portion of ice we would have water. This means that we have considered the worst case scenario by assuming fresh water, and for more salty water the freezing does not penetrate as deeply as we computed, which benefits our hypothesis. Secondly, Zotikov concluded from his calculations (5) that Lake Vostok has nearly fresh upper water. The salt content in Lake Vostok is probably a function of water depth with the bottom water being saltier than the upper water.

There is no thermal convection in the Antarctic glacier (cf., 19), but there can be convective heat transport due to the ice spreading under gravity. Our model does not include the convective term $c\rho V\nabla T$. We will show below that this term can be neglected in our case. Since we are interested in the initial freezing only, it was possible to apply the Stefan condition and to estimate analytically the critical total ice thickness. After reaching this critical thickness, the phase transition front stops and reverses its motion, i.e. slow basal melting begins. We have analytically obtained its value to be about 1 km. Our more sophisticated computations gave even a lower value of 600 m. Dividing the maximum ice thickness of 1.5 km in our computations by the current 900 km half-width of the Antarctic glacier, we arrive at the dimensionless parameter 1/600. This parameter in our case is far below the critical value (5, p. 261-262) and hence the convective heat transport caused by the ice spreading can be neglected. Note that at the critical value of this parameter, the convective heat transport comprises only about 10 % of the total heat transport (5, p. 261-262). Therefore, it is more important in this problem to take into account the latent heat of freezing. The choice of initial glacier width equal to the current width reflects the assumption that the snowfall began in the whole area.

Since the goal of this study was to compute the heat transport only in the ice above the lake, we have modeled convection in water by increasing the computed effective $\nabla T_{conductive}$: $\nabla T_{conductive\ effective} = \nabla T_{conductive} + q_{convective}/\lambda_{water}$. Omission of the convective term may give increased water temperatures, but it did not influence the ice temperatures and the front positions, which are the main objectives of our work. The lower boundary heat flow would be transmitted unchanged via water to the front, since we have chosen the water initial temperature distribution to be in equilibrium with this heat flow: $\lambda_{water}\nabla T_{conductive} = q_{internal}$. Note that water at the bottom of the Antarctic lake Vanda (under the perennial 3.5 - 6 m ice cover) has an unusually high temperature of about 25 C due to the absence of convection in the lower portion of the lake, owing in turn to the high salinity gradient. The depth of Vanda's water is $\approx$ 80 m.

Nonlinear dynamical numerical model

The analytical Stefan equation via the err-function is not applicable in our case, since it requires a constant upper boundary temperature. This argues for the necessity of a numerical model to treat the phase transitions. The unknown phase transition boundary, described by the equation $F(x,y,\tau) = 0$ is at the temperature $T_{phase} = -H/1149$, where H is the ice depth in meters. The depth dependence was taken for pure water ice and corresponds to a Clausius-Clapeyron gradient of $8.7 * 10^{-4} C/m$ (20).

We solved numerically the following nonlinear system of partial differential equations:

$$c(T,x,y)\rho(T,x,y)\frac{\partial T(x,y,\tau)}{\partial \tau} = \frac{\partial(\lambda(T,x,y)\partial T(x,y,\tau))}{\partial x \partial x} + \frac{\partial(\lambda(T,x,y)\partial T(x,y,\tau))}{\partial y \partial y}, \text{ where}$$

$$T(x,y,\tau) \neq T_{phase},$$

$$T(x,y,0) = T_0(x,y), \tag{1}$$

$$\left.\frac{\partial T}{\partial x}\right|_{x=0} = \left.\frac{\partial T}{\partial x}\right|_{x=d_1} = 0,$$

$$\lambda \left.\frac{\partial T}{\partial y}\right|_{y=d_2} = q_{internal},$$

$T(x,0,\tau) = \phi(x,\tau)$ - the upper boundary condition.

The upper boundary temperature is given on the moving upper boundary. We derived that the unknown position of this boundary satisfies the equation:

$$G(\tau) = \int RATE(G(\tau))d\tau,$$

where τ is the time variable, x is the horizontal variable, y -vertical variable, d_1 - width of the computational domain, d_2 - depth of the computational domain, T - temperature, λ - thermal conductivity, c - heat capacity, ρ - density, $q_{internal}$ - geothermal heat flow and $RATE$ - the variable snowfall rate.

The temperature dependence of the thermal conductivity and heat capacity of ice was taken from (18):
$\lambda_{ice} = 2.55 * (1. - 0.0044 * (T - 30.))$ in J/(m*s*K),
$c_{ice} = 920. * 1880. * (1 + 0.004 * (T - 30.))$ in $J/(m^3 * K)$.
If a point P belongs to the front $F(x,y,\tau) = 0$, the two following equations are valid:

$$T(x,y,\tau) = T_{phase},$$

$$Q\frac{\partial F}{\partial \tau} = (\lambda \nabla T|_{P+0} - \lambda \nabla T|_{P-0}, \nabla F),$$

where $Q = 333.2 * 10^6$ is the latent heat of water freezing in J/m^3, $P+0$ is the index for the function whose variable trends to a point on the phase transition front from the warmer temperature region, and $P-0$ denotes the opposite case. Note that d_2 is increasing during our computations, since the whole domain, where the problem is solved is changing in time due to the accumulation of ice via the snowfall.

The enthalpy method was used to solve the problem (1) numerically. The enthalpy was smoothed over a small temperature interval of $(T_{phase} - E, T_{phase} + E)$ with a linear function ($E = 0.02$ C). Physically, this reflects the fact that freezing does not occur at a fixed temperature, but over a small temperature interval (cf., the concept of unfrozen water, (21)). Mathematically, the accuracy of the solution with different E from the range we considered in our numerical experiments is within the accuracy of the finite difference scheme.

The space grid was chosen so there would be 2 - 4 grid nodes in the smoothing interval at each timestep. This choice has been confirmed by numerical experiments (17, 19, 21, 22). The heat capacity function was also interpolated linearly over the phase transition interval. We constructed a finite difference scheme and solved the resulting nonlinear system of discrete equations iteratively on each time step. The linear with depth interpolation of the temperature field was used to find the position of the phase front. The accuracy of the computed front was equal to the vertical step of the grid.

Though our numerical model allows for the emergence of a phase transition front, we took the initial freezing front at the maximum possible seasonal depth of 4 m (the worst case scenario which alleviates freezing) compared to the modern lakes near the currently warmer Antarctic coast. The initial temperature was chosen as a piecewise linear with depth function. In the upper ice this linear function connected the initial upper boundary temperature of -12 C and 0 C at the seasonal front's depth. The temperature profile was chosen in water according to the $\lambda_{water} \nabla T = q_{internal}$. This reflects the steady state case of the lake being on the surface for a long time before perennial glaciation. Though we have developed a 2D algorithm and the corresponding program, for this case we have used only its 1D option. The program is available from the first author upon request.

Numerical Results

We computed that the maximum depth of 53 m for Lake Vostok freezing was reached after 3300 years from the beginning of Antarctic glaciation for the average geothermal heat flow of 55 mW/m^2 and the initial upper boundary temperature of -12 C (Fig 1, dotted line). The current Vostok's water depth at a single point is about 500 m (4). The freezing front penetration into the lake is slow, with a speed not exceeding about 2 cm/yr for this case.

We have performed the numerical experiments for the correlation of the front position and the basal heat flow. The deepest freezing front penetration was computed for the lowest heat flow of Europa (Fig. 1, dot-short dash line). For the lowest estimate for its internal heat flow (20 mW/m^2, (23)), we computed the maximum freezing front penetration into the water to be $\approx$ 69 m. It is reached in $\approx$ 8000 years from the onset of glaciation.

Due to the heat released from the friction of a glacier against bedrock, the lower boundary heat flow on Earth can be as high as 100 mW/m^2, according to Zotikov's calculations (5). The same geothermal heat flow was directly measured by Zotikov (5) at the bottom of lake Figurnoe (with $\approx$ 150 m deep water under $\approx$ 3 m of ice), which is situated at the Antarctic coast in Banger Hills oasis. For this elevated heat flow of 100 mW/m^2 we computed the maximum freezing depth to be $\approx$ 39 m reached in only $\approx$ 1750 years from the onset of Antarctic glaciation (Fig. 1, solid line).

As a comparison, the maximum depth of the freezing front for the average Mars' internal heat flow of 30 mW/m^2 (the lower estimate for Mars, (24)) was obtained to be $\approx$ 63 m reached in about 5250 years (Fig. 1, long dash line). At that time the total ice accumulation was only about 900 m. In all of the above computations the initial upper boundary temperature was -12 C. Note that we made computations for Mars' and Europa's internal heat flows, but not for their past climatic conditions. We have demonstrated numerically that the internal heat flow begins in a relatively short time to play a more important role for the freezing front depth (i.e., for the water depth) than the decreasing external temperature. Given the uncertainty of the past climate and the dominance of the internal heat flow, our model is applicable to these bodies.

The computed ice accumulation from the freezing of the lake and from snowing is shown in Fig. 2 for the terrestrial case of 55 mW/m^2 internal heat flow. Note that the total ice thickness at the time of the onset of basal melting for the average terrestrial heat flow of 55 mW/m^2 was only about 600 m and that the total ice thickness is not a linear function of time. Plots on Fig. 1 (dot-long dash line for -10 C and dotted line for -12 C) with the different initial upper boundary temperatures (and the same basal heat flow of 55 mW/m^2) illustrate the dependence of the numerical solution on this input parameter. Our numerical experiments have shown that changing -12 C to -10 C for this model input parameter does not change the solution much. The maximum freezing front penetration is $\approx$ 43 m for the initial upper boundary temperature of -10 C.

The longer dynamics of the phase transition front, where freezing reverses into melting, is shown on Fig. 3. The upper boundary condition is shown in Fig. 4. The computed critical water depth is applicable to other Antarctic lakes under a km-thick ice cover.

We realize that the system Lake Vostok-the ice sheet above it behaves in more complicated ways than described in our model. For example, rocks were found recently in ice at the depth of about 3600 m. The ice scrapes the bedrock on its way from the divide to the lake, therefore gathering and carrying rocks with it. The distance of Lake Vostok from the divide is only about 120 km.

Exobiological Implications for Mars

Viable microorganisms (fungi, bacteria, yeasts capable of growth in a conducive medium) have been isolated from Vostok ice cores at depths of 2.4 km, corresponding to ages of about 200,000 years (25, 26). As a conducive medium, the potato broth was used in Abyzov *et al.* experiments (26). Although algae, specifically diatoms, have been found in these cores, none have yet been cultured. The depth to which viable organisms can be found is not yet known, but Abyzov and colleagues are now attempting such experiments with the basal ice cores (depths of about 3,600 m), estimated to be about 400,000 years old (27). Because of the vertical component of the ice flow, the movement of such trapped microorganisms is downward, and the basal ice upon melting seeds the lake with these microbes.

A very interesting implication of our model is that live organisms and/or their remnants in Vostok waters, could be much older than the age of the basal ice, and even older than the age of the Antarctic ice sheet, i.e. older than 5 - 30 Myrs. In terms of evolution of life on Earth, this time period is rather recent, and assuming that this lake was a productive ecosystem, remnants of its biota must certainly be preserved in its sediments. Under thick ice it would have become dark, and any existing photosynthetic ecosystem would certainly have perished and have been replaced by a lithotrophic system (one living on inorganic chemicals generated via geothermal reactions). In addition, the lake is continuously seeded with dust and other mineral particles from the upper ice, which replenish the sediments and can serve as food for the microbes. For example, rock breathing microorganisms (28, 29) could still be living in Lake Vostok's water and sediments. If there are no hydrothermal inputs to the lake, there would be little energy available, and a starvation-survival mode would almost certainly set in.

If this is so, then it could be a repository for an ancient ecosystem that has been isolated from the present day Earth for millions of years. Depending on the energy sources available to this hidden ecosystem, the nature of any surviving life could range from something similar to that found in deep sea hydrothermally driven ecosystems, to a very minimal ecosystem, in which virtually no energy is available.

Though little is known about the thermophysical characteristics of the Martian subsurface until direct studies will be conducted by penetrators and/or drilling, are a few models predict basal melting of the assumed 4 - 6 km thick north polar cap (e.g., (30), (12), (15)). The north cap consists mostly of water ice. Recent measurements of Mars Orbiter Laser Altimeter (MOLA) on Mars Global Surveyor implied that the north cap is thinner (maximum thickness about 3 km, 16). The cap has an average thickness of 1.03 km (16). For most plausible values of thermal conductivity of the cap, this ice thickness is not sufficient to have basal melt under it. Nevertheless, this thickness (being more than the critical value of 600 m we obtained in our computations) is sufficient to apply our Vostok model. Then, if there is water under the Martian north cap, it can originate only from an initially open lake.

Both Mariner 9 (the first US orbiter of Mars) in 1971 and Viking in 1976 saw CO_2 ice on the south cap. Still the south residual cap is thought to be composed mostly of H_2O ice also, based on the interpretation of the ground-based observations of a global burst of H_2O vapor into Martian atmosphere in 1969 during the southern summer (31, 32). This was interpreted that the south polar cap had a thin veneer of CO_2 ice on top of permanent H_2O ice. The thickness of the south martian polar cap is still uncertain with the range from a few meters to several kilometers. Mars Orbiter Laser Altimeter will determine its thickness in spring 1999. If the south cap is also about km-thick, our Vostok model is applicable as well. Then the situation could have been similar to the formation of Lake Vostok with plausible ancient microorganisms and/or their remnants in the Martian sub-polar waters. If, on the contrary, the south cap is a few meters thick, the studies (6) of lake Vanda and Bonney, and other Antarctic lakes under the perennial 3.5 - 6 m ice cover are very useful as an analog for Mars.

The current obliquity of Mars is 25.19 deg which is close to 23.45 deg for Earth. Mars has experienced periodic variations in insolation similar to Milankovich's cycles for Earth (33, 34). This may have caused the growth of thick polar caps similar to the Antarctic ice. Calculations (15) for the basal melting of a polar cap on Mars assumed a traditional hypothesis that melting results from geothermal heat flow under sufficiently thick polar ice deposits. He concluded that the estimated 1 - 2 km thickness of the south martian polar cap is too small for the basal geothermal melting since the calculated position of the melting isotherm is likely to be located below the south cap. Importantly, our model computations WEAKEN the CONSTRAINT on the ice thickness necessary for having water under it, if water was initially on the surface. The total ice thickness computed with Mars' internal heat flow for the time when the maximum depth of freezing was reached is only about 900 m. Therefore, we include martian south polar cap in our considerations as well.

As follows from our computations for Lake Vostok, a potential martian lake under the north or the south polar cap could have been an open lake on the surface of Mars in the past. Within Martian valley network in polar regions there are two very large valleys: Chasma Boreale in the north (80 N to 85 N) and Chasma Australe in the south (76 S to 86 S). Chasma Boreale has a width of up to 350 km and extend in length for about 600 km (16). These valleys can be viewed as morphologic evidence for possible existence of lakes in polar regions on Mars BEFORE the formation of martian polar caps. This means that areas beneath martian polar caps are good sites to look for the remnants of ancient life on Mars and maybe even for live microorganisms that existed in water well before its glaciation from the top and were preserved in water shielded from Martian cooling environment by blanketing polar ice. If there are lakes under the martian polar caps, they, according to our model, might be the OLDEST aquifers on Mars, and perhaps the most accessible sources of liquid water and extant or extinct life.

Experimental tests

We suggest measurements of the lake's salinity, water depths at different locations, the thickness of the lake sediments and measurements of the microbial cell density (including their remnants) in water and sediments that will possibly support one of the two origin hypothesis for Lake Vostok. Paleobiological test (determining the age of organisms and their remnants in sediments) will also be very useful.

The conclusion about Lake Vostok having salinity less than 15 per mil (about 2 times less than the sea water, i.e., being almost fresh) was obtained first by Zotikov on theoretical grounds (5). He considered the upper ice to be floating on the lake because the lake's width (about 50 km) is much greater that the ice thickness (about 3.7 km). Then he calculated the buoyancy force. Being denser and thus producing a larger buoyancy force, saltier water would push the water-ice interface higher.

There still might be some salts present in the lake and in order to know the origin of the lake it is important to know how much. Therefore, we propose sensitive measurements of the lake's salinity. The water freezes under the thinner ice cover (water "sink") and the newly formed ice begins to flow with the ice above it, ultimately ending up in the ocean. At the same time, the source of water is the melting of ice under the thickest ice cover, where the ambient ice temperature is the highest and the melting temperature is the lowest because of the pressure induced melting. During the freezing process, salt is mostly left behind in water (freezing is a very good distillator).

It can be calculated how much time is needed to obtain the salt content in water (which will be measured), if we assume that all water came from melting of the ice above. The salinity of ice is known, since the ice core was extracted. The steady-state melting rate was calculated by Zotikov in (5). If the calculated melting time is more than the age of the Antarctic ice sheet (5 - 30 Myrs), then there was initial salt present in water. (The ice was not able to melt that long - it just did not exist that long). Therefore, the lake did not originate from the ice basal melting, but was initially a relatively salty lake on the surface. For other calculated times the conclusion about the lake's origin probably cannot be drawn using this method. The salinity is usually measured by measuring the electrical conductivity.

These experiments can be implemented in situ on a miniature hydrorobot, a part of a bigger (about 0.5 m long) cryorobot, within the proposed Vostok-Europa project. This project is now being studied for the proposed Europa mission with its first application in Lake Vostok. The cryorobot will electrically melt its way through the last 300 m of ice above the lake with the upper ice melted by hot water (the last method being less expensive). The ice would freeze above the cryorobot. Then the hydrorobot will be released in water.

Since a martian pole experiences continuous sunlight for about two times longer than the Earth's poles (Mars' year is $\approx$ 1.88 Earth year), there is sufficient daylight time to conduct cryorobotic studies of the martian icy subsurface. This can be done during the future Mars Surveyor missions. The cryorobot can be delivered to the polar regions either by a rover, or by a penetrator. The penetrator would generate heat upon impact and the cryorobot can use this initial ice melting. The drilling site can be determined from preliminary radar sounding studies.

Conclusions

We obtained the surprising numerical result that the freezing front reversed its motion down in a relatively short time from the onset of perennial glaciation, when it still has not penetrated deeply enough to freeze Lake Vostok to the bottom (if it were an open lake initially). This is due to a combination of physical factors: thermal blanketing effect of ice, which shields water from cooling environment, the sufficiently high net rate of ice accumulation and relatively high (compared to the heat capacity) latent heat released upon water freezing. We performed numerical experiments on the sensitivity of the solution to Earth's, Mars's and Europa's values of the internal heat flow. We showed that the depth of the phase transition front penetration increased from 53 m to only 69 m when the geothermal heat flow was changed from 55 mW/m^2 (average terrestrial value) to 20 mW/m^2 (lowest estimate over Europa's history).

For these computations we have developed a numerical model, using the nonlinear dynamical Stefan formulation for the phase transition problem with the thermophysical characteristics dependent upon temperature, ice accumulation via the snowfall with the temperature dependent rate and the phase transition temperature dependent upon pressure. Therefore, it is probable that the large Lake Vostok has originated not from basal melting but was an open lake on the continent before the perennial glaciation of Antarctica, and has never frozen to the water bottom.

This means that the water in the lake could be older than 5 - 30 Myrs, which is the estimated age of the Antarctic ice sheet. Therefore, our hypothesis of an initially open lake has enormous biological and paleogeographical implications. The lake sediments might still contain remnants of ancient fishes and other unusual species, not only the microorganisms being seeded from the upper ice. We also have proposed experimental tests for our origin hypothesis. According to our model, there could be similar lakes under Mars' polar caps, which were open lakes in the past and did not originate from the basal melting.

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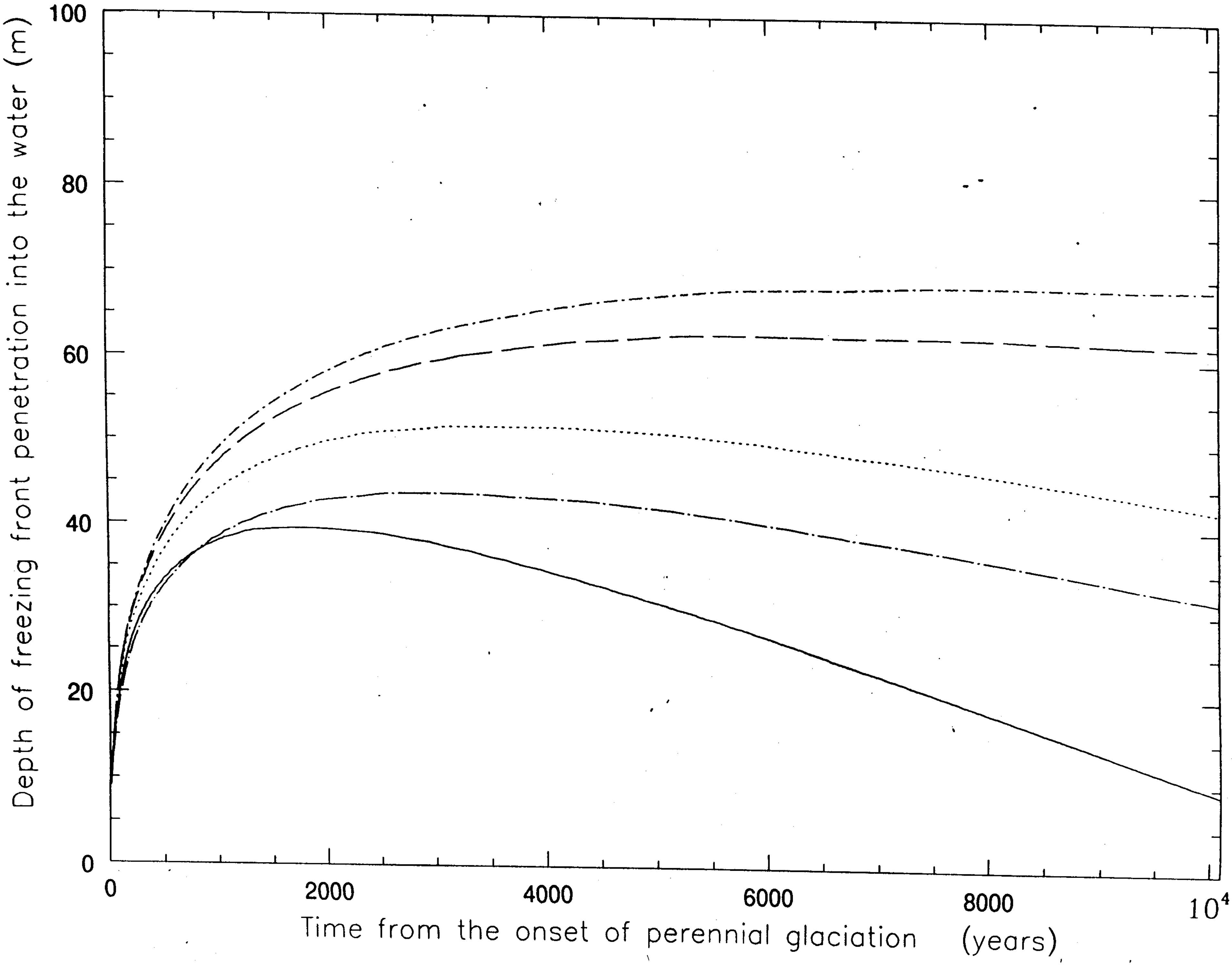
Figure Captions

Fig. 1. Depth of the freezing front penetration into the lake relative to the initial water surface from the beginning of Antarctic glaciation for the initial upper boundary temperature of -12 C and the average geothermal heat flow of 55 mW/m^2 (dotted line), Mars' internal heat flow of 30 mW/m^2 (long dash line), for the lowest estimate of Europa's heat flow of 20 mW/m^2 (dot-short dash line) and the elevated geothermal heat flow of 100 mW/m^2 (solid line). Dynamics of the freezing front for the initial upper boundary temperature of -10 C and the same basal heat flow of 55 mW/m^2 is shown by the dot-long dash line.

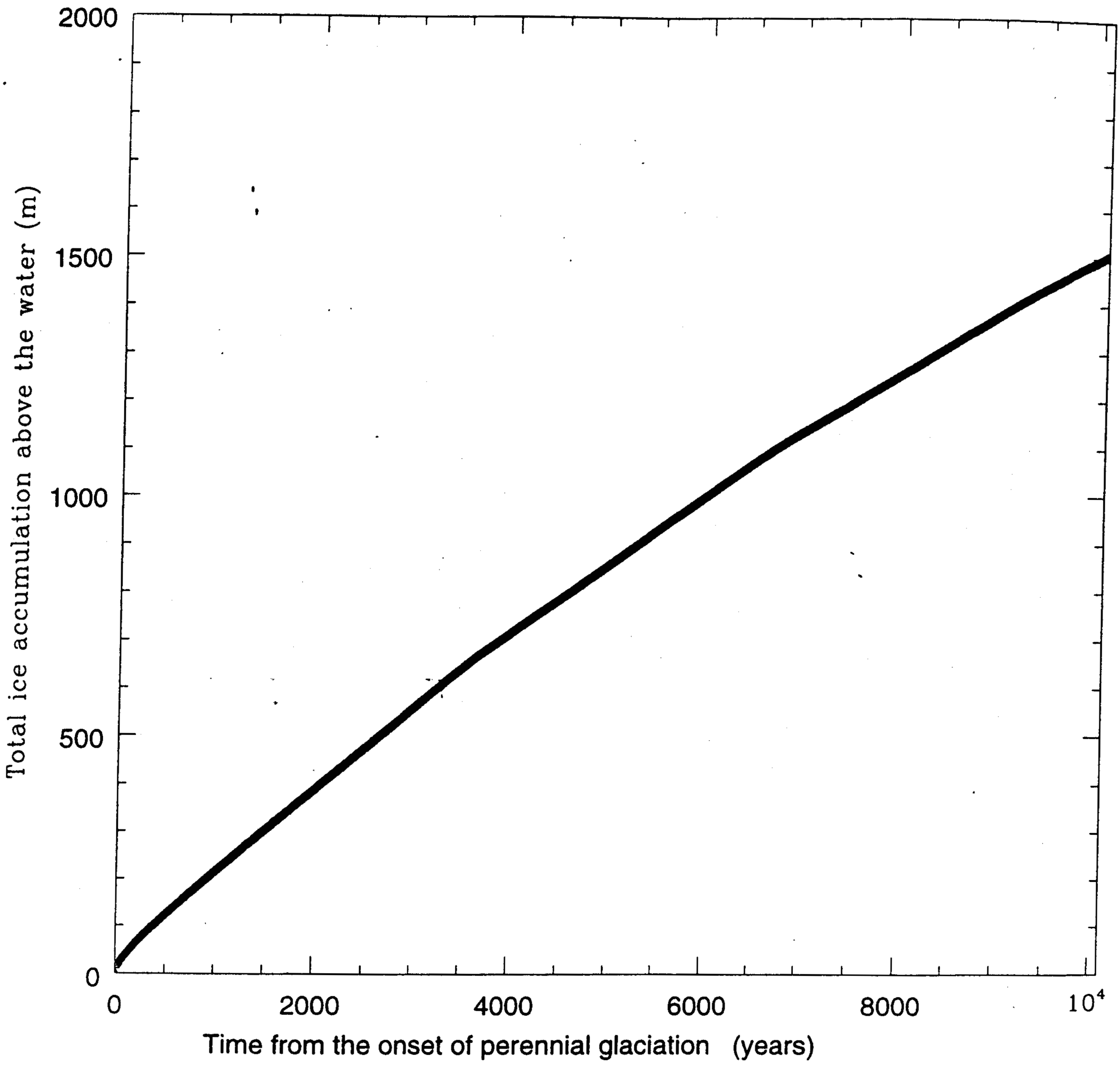
Fig. 2. The computed total ice accumulation from the freezing of the lake and from snowing for an average terrestrial internal heat flow of 55 mW/m^2.

Fig. 3. The depth of freezing front penetration into the lake relative to the initial water surface during 40,000 years from the beginning of Antarctic glaciation. The initial upper boundary temperature is -12 C and the geothermal heat flow is 55 mW/m^2.

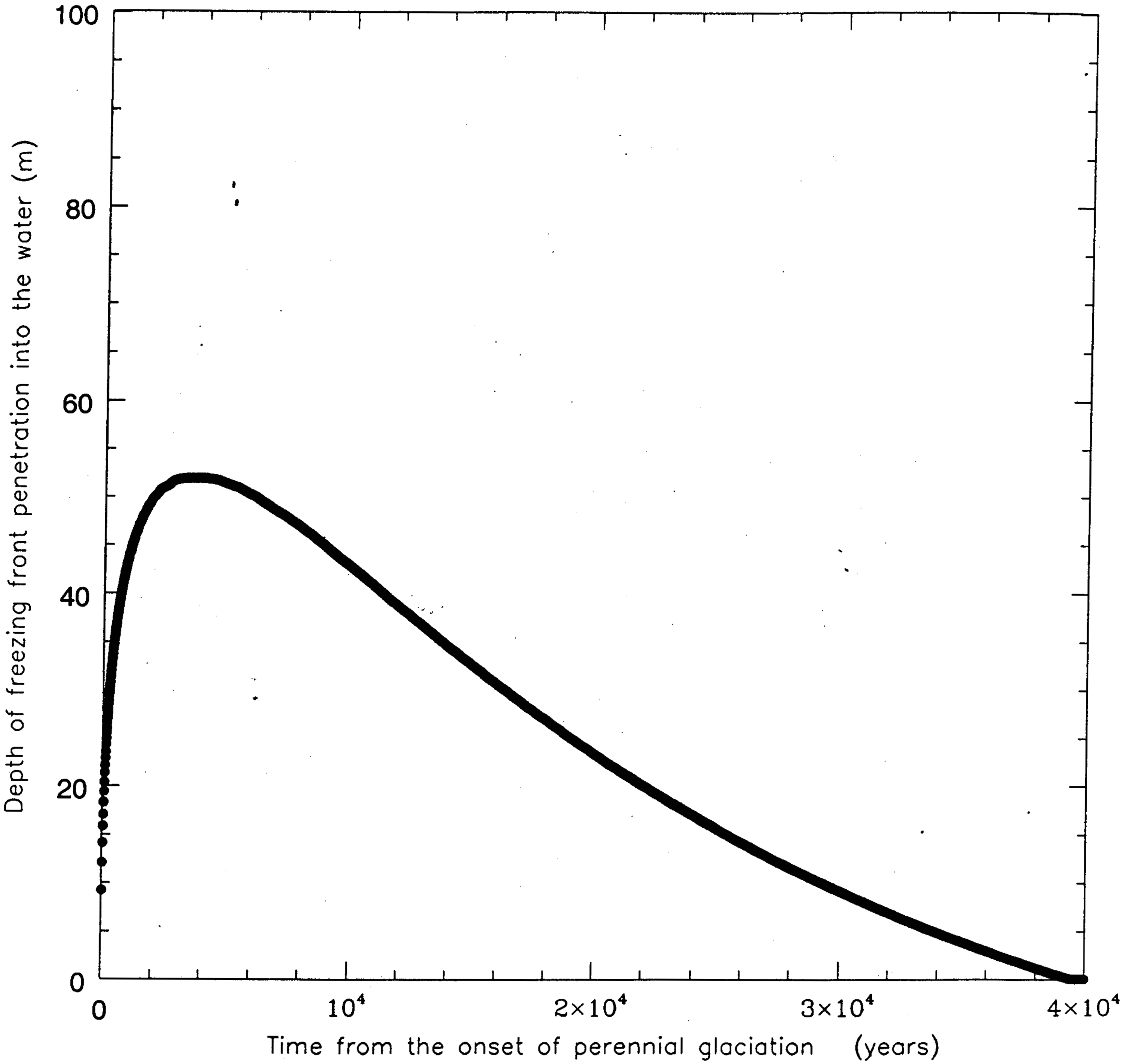
Fig. 4. The computed upper boundary condition, which we used in most of our program runs.



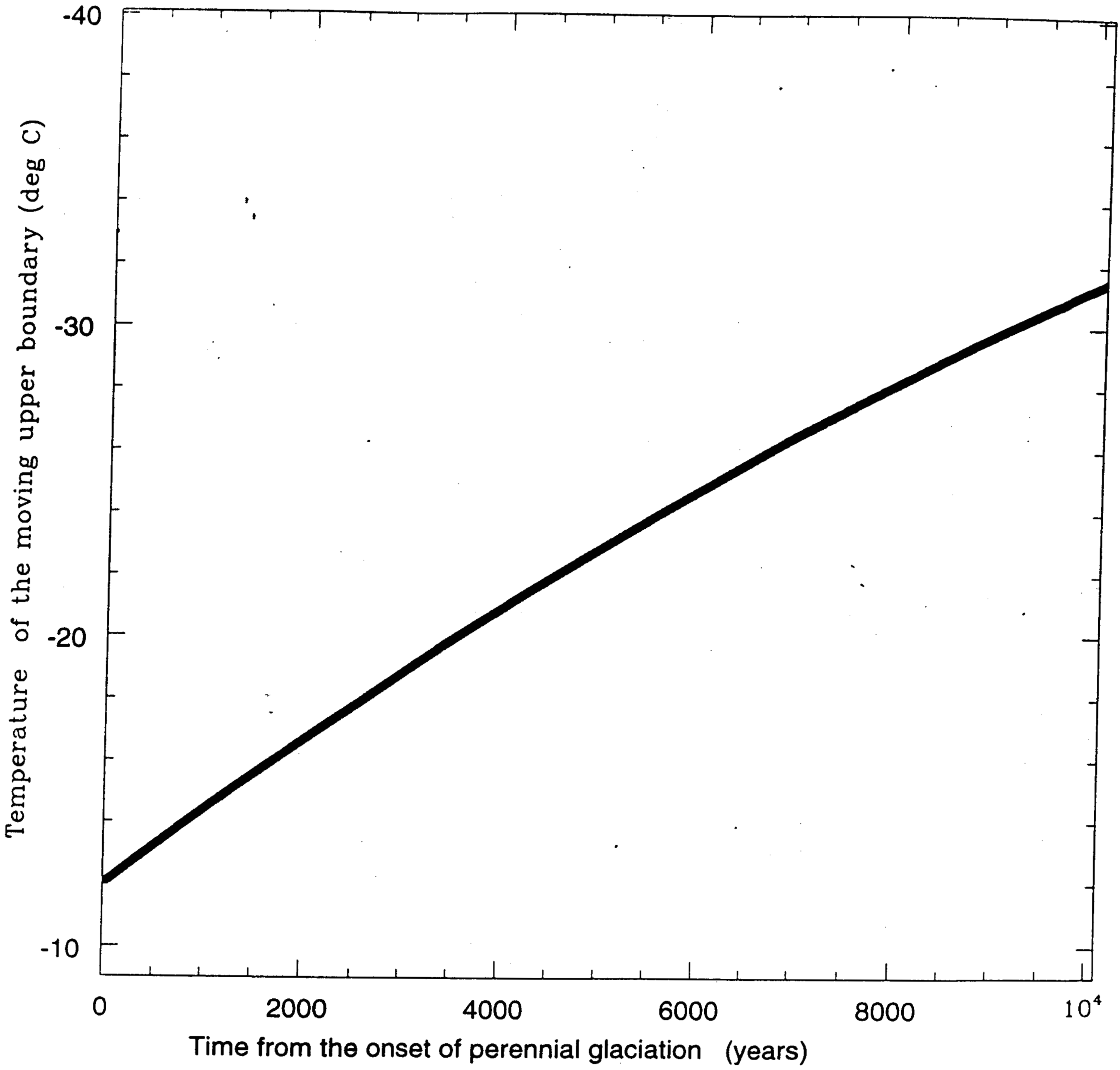
100
80
60
40
20
0
0
2000
4000
6000
8000
10^4
Depth of freezing front penetration into the water (m)
Time from the onset of perennial glaciation (years)



Durham et al. Fig 2



100
80
60
40
20
0
Depth of freezing front penetration into the water (m)
0
10⁴
2×10⁴
3×10⁴
4×10⁴
Time from the onset of perennial glaciation (years)



-40
-30
-20
-10
Temperature of the moving upper boundary (deg C)
0
2000
4000
6000
8000
10^4
Time from the onset of perennial glaciation (years)

Fig. 4